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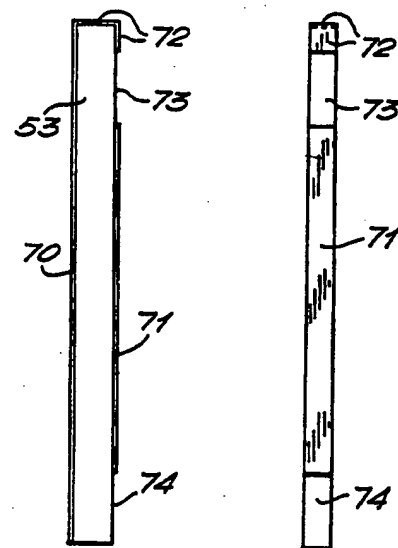
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(54) Title: ULTRASONIC ELECTRO-ACOUSTIC TRANSDUCERS

(57) Abstract

An ultrasonic electro-acoustic transducer (50) comprises an electro-acoustic element (53) having an elongate working face, bearing a first electrode structure (70), and a second face spaced from the said working face and bearing a second electrode structure (71). Electrical driving circuitry is connected to the first and second electrode structures for applying electrical driving signals therebetween to cause the element to vibrate so that ultrasonic acoustic waves are propagated, into a medium coupled to the said elongate working face, in a direction away from that working face. The said electro-acoustic element, electrode structures and driving circuitry are such that the effects of the said electrical driving signals differ at different locations along the said working face so as to counteract destructive interference effects that would otherwise occur at points, in the said medium, along a target line parallel to the said longitudinal axis and spaced at a predetermined distance in the said direction from the said working face.



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ULTRASONIC ELECTRO-ACOUSTIC TRANSDUCERS

The present invention relates to ultrasonic transducers for use, for example, in detecting the presence of an object in a predetermined region without
5 contacting the object.

Many methods have been proposed for detecting the presence of an object within a predetermined area without contacting the object concerned. These methods include radar, sonar, light curtains and other optical
10 techniques. In a sonar arrangement, for example, acoustic waves are emitted from a transmitter device in the direction of the object, and a receiver device, generally located adjacent to the transmitter device, is used to detect waves reflected back from the object
15 concerned, and to provide an electrical output signal in response to those reflected waves. By analyzing the output signal it is possible to determine whether or not an object is present within the monitored area of the arrangement.

20 In the majority of applications in which acoustic waves are employed to detect the position of an object the dimensions of the transmitter and receiver devices are negligible compared to the range (measured from the devices) of the object to be detected. However, in
25 certain applications it may necessary to position the transmitter and receiver devices relatively near to the object to be detected, so that the dimensions of the devices are no longer negligible in comparison with the object range.

30 One such application involves the use of ultrasonic acoustic waves to detect the presence of threads in textile machinery. In such machinery the space available for mounting the transmitter and receiver devices is limited, and the relatively low ultrasonic wavelengths
35 (for example 0.33mm) must be used to detect the threads (having diameters as small as 0.1 mm) satisfactorily. In such circumstances the returned acoustic waves are weak,

so that operation over long ranges is not generally possible.

In such use of ultrasound to detect threads an additional problem arises in that the position of the thread (as it is supported in the machinery) may vary laterally by distances that are large compared to the diameter of the thread itself. Such variation is practically inevitable and it is accordingly required to be able to detect the position of the thread reliably over a predetermined region that is large compared to the thread diameter.

In an attempt to satisfy this requirement an elongate ultrasonic transducer could be disposed with its longitudinal axis perpendicular to the axis of the thread to be detected. Such a disposition can in principle permit lateral variation of the thread position to be accommodated.

However, with such an elongate transducer arrangement it is found that the range of lateral positions over which the thread can be detected reliably may be much less than the length of the elongate transducer, for reasons that will be explained in detail hereinafter with reference to Figure 9.

It would in principle be possible to simply increase the length of the transducer to increase the range of positions in which the thread can be detected, but such a transducer of increased size would be more costly, and in certain applications space is not available to mount such a large transducer. In addition, if the length is increased it is found that the received signal amplitude may become too weak for reliable detection because the generated acoustic energy is distributed over a wider area.

It is desirable to provide an ultrasonic transducer device in which the above-mentioned range can be increased without increasing the device dimensions unacceptably.

According to the present invention there is provided an ultrasonic electro-acoustic transducer comprising an electro-acoustic element having an elongate working face, bearing a first electrode structure, and a second face
5 spaced from the said working face and bearing a second electrode structure;

there being electrical driving circuitry connected to the first and second electrode structures for applying electrical driving signals therebetween to
10 cause the element to vibrate so that ultrasonic acoustic waves are propagated, into a medium coupled to the said elongate working face, in a direction away from that working face;

and the said electro-acoustic element,
15 electrode structures and driving circuitry being such that the effects of the said electrical driving signals differ at different locations along the said working face so as to counteract destructive interference effects that would otherwise occur at points, in the said medium,
20 along a target line parallel to the said longitudinal axis and spaced at a predetermined distance in the said direction from the said working face.

In a method of detecting a filamentary body, supported so that it extends longitudinally across a
25 predetermined position, ultrasonic acoustic waves are transmitted towards the said predetermined position, transversely with respect to the longitudinal axis of the said filamentary body, and such waves diverted back by the filamentary body, from the said predetermined
30 position, are monitored. Preferably, in such a method a transducer as set out above may be used to transmit and detect such acoustic waves.

Apparatus may be provided which includes means for supporting a filamentary body so that it extends
35 longitudinally across a predetermined position, relative to a support portion of the apparatus, and monitoring means including ultrasonic transducer means, preferably

constituted by a transducer as set out above, mounted on the said support portion and operable to transmit ultrasonic acoustic waves towards the said predetermined position, transversely with respect to the longitudinal axis of such a body so supported, and to detect such waves directed back, by such a body, from that position.

5 waves directed back, by such a body, from that position.

For a better understanding of the invention, and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings, in which:-

5

Figure 1 shows a schematic perspective view of a draw frame of a textile machine;

Figure 2 shows a schematic perspective view of a draw frame, of a textile machine, including apparatus in which a device embodying the present invention is incorporated;

10

Figure 3 shows a schematic plan view of a component of the Figure 2 apparatus;

Figure 4 shows a block diagram of electronic circuitry employed with the apparatus of Figure 2;

15

Fig. 5 shows a diagrammatic side view of an ultrasonic transducer device embodying the present invention;

Fig. 6 shows a more detailed longitudinal sectional view of the device of Fig. 5;

20

Fig. 7 shows a sectional view of the Fig. 6 device, as seen along a line VII-VII in Fig. 6.

Figs. 8(A) and 8(B) show respective side and rear elevational views of parts of the transducer device of Figs. 6 and 7;

25

Fig. 9 shows a schematic perspective view of a thread detector arrangement including an elongate ultrasonic transducer not in accordance with the present invention;

Fig. 10 is a graph illustrating the amplitude of acoustic waves produced by the transducer of Fig. 9 as a

30

function of position along the length of the transducer;

Fig. 11 is a graph corresponding to Fig. 10, but illustrating characteristics of the device of Figs. 6 and 7; and

5 Figs. 12 to 15 show diagrammatic representations of alternative forms of the parts of Figs. 8(A) and 8(B).

Figure 16 is a polar plot showing amplitude variation of acoustic waves produced by the device of Figs. 6 to 8;

10 Figure 17 shows a diagrammatic view illustrating transmission and reflection of acoustic waves to and from the device of Figs. 6 to 8; and

Figures 18 and 19 show respective diagrammatic views corresponding to Fig. 17, for use in illustrating effects
15 of variation in dimension of the transducer device.

The main structure of the draw frame of Figure 2 corresponds to that of Fig. 1, but Fig. 2 shows the aforementioned pigtail 5a and balloon ring 5b. The draw frame of Fig. 2, however, is provided with a support
20 member in the form of a mounting bar 2 which extends along the complete length of the textile machine, between each outcoming thread 3 and the main body of the machine. A sensor unit 1 is mounted, on the bar 2, so as to be operative in a horizontal plane which is parallel to the
25 mounting bar 2 and intersects the thread 3 at a position between nip point 4 (between rollers 204) and the pigtail 5a. At such a position, angular and lateral movement of the thread is within acceptable limits and there is sufficient space for mounting the sensor unit 1.

30 An elongate ultrasonic transducer device 6 is mounted in the sensor unit 1 so that the longitudinal axis of that device 6 lies in the said horizontal plane, at an angle of approximately 45° to the axis of the mounting bar 2. It will be appreciated that, over a
35 complete textile machine, individual sensors will be spaced apart from one another according to the spacing of threads on the machine.

In Figure 3 the sensor unit 1 can be seen in more detail. It is preferably attached to the bar 2 by means of a plug attachment 8, and has an indicator light 7 which is preferably an LED.

5 The position and angle of the thread 3 is likely to vary. It is thus not appropriate to focus the beam of ultrasound emitted from the transducer device 6. Instead, the transducer device 6 is designed to ensure that there are no 'dead spots' within a predetermined
10 region in which the thread is expected to be found.

It is arranged that the thread 3 will be between 27.5 and 42 mm away from the sensor unit 1 and will have a lateral movement of ± 6 mm in the horizontal plane. The angular displacement from the vertical is expected to
15 be $\pm 10^\circ$. This movement creates a notional rectangle (in the horizontal plane) in which the thread is expected to be found, with its nearest edge parallel to the longitudinal axis of the transducer device 6. This edge is 27.5 mm away from the transducer device 6 and is 12 mm
20 long. The rectangle has a length of 14.5 mm. In three dimensions, the volume in which the thread 3 is expected to be found is a notional parallelepiped whose dimensions are the same as for the rectangle above, but where depth is defined by the depth of the field of view of the
25 transducer device 6.

Figure 4 shows a block diagram of electronic circuitry involved in the detection of the thread by the sensor unit 1.

This circuitry is divided between a control board 9,
30 which controls 16 such sensor units and a sensor board 10 located within the sensor unit 1.

The operating frequency is chosen to satisfy the requirements that i) the sound is not heavily attenuated by air as it travels through the greatest distance (85
35 mm), and ii) the wavelength is comparable to the diameter of fine threads (0.1 mm).

Further, since a single transducer is to be used as

both the transmitter and receiver for the pulse-echo technique, then there should be a sufficient number of cycles between transmission and reception for the transmission oscillation to decay. This will depend on
5 the operating frequency, f , the damping characteristics, Q , and the magnitude of the received signal. For a closest approach of 27.5 mm, the decay time must be 150 μ s or less.

Bearing in mind the variation of the received signal
10 with thread diameter, the wavelength (and frequency) of operation are chosen to achieve a situation in which the reduction in reflection with reducing thread diameter is balanced by increase in reflection, or backscatter, produced by interference effects, thereby obtaining an
15 overall reflection coefficient which is largely independent of thread size. The selected operating frequency is 1.0 MHz. This has a wavelength in air of 0.33 mm, comparable to normal thread diameters. At this frequency, there are 150 cycles between transmission and
20 reflection, enough to allow the use of a single transducer in the pulse-echo technique. At this frequency, the reflected signal is largely independent of thread diameter.

A microprocessor 11 activates the sensor board 10
25 via a driver 12. This has the effect of driving an oscillator 13 which generates a signal which is tuned to the frequency of the transducer 6 (approximately 1MHz). This signal is amplified by a driver 14 and applied to the transducer 6 as a burst of 30 half-cycles of
30 amplitude +38V.

The transducer is thereby caused to emit a burst of acoustic waves which are reflected by the thread 3 (Fig. 3). The reflected signal is received by the transducer 6 which is thereby caused to generate an electrical signal.
35 This detected signal is amplified by a factor of 3500 by a band-pass amplifier 15 which has a Q of 5.

This thread sensing system is designed to

distinguish the reflection from a thread - a wavetrain or burst of 30 pulses at 1 MHz - from a sharp electrical spike such as electrical noise produced by a switched mode power supply used to power a drive motor on the textile machine.

The filtered output of amplifier 15 is sent via a line driver 16 to a detector 17. The detector 17 detects whether the signal exceeds a predetermined threshold a given number of times in a given number of consecutive 1 μ s periods.

Because the amplifier 15 has a relatively wide band pass, an electrical spike will retain its sharp form and thus will cross the threshold only once or twice during a time interval in which the thread reflection will cross the threshold at least ten times. This allows the reflected signals to be distinguished clearly from such electrical noise.

The signal from the detector 17 is sent to the microprocessor 11 for further analysis.

The thread detection system must sense the small reflected signal from a thread, but should not sense various other signals from textile machinery and electrical interference, to minimise the chance of such noise giving a false detection result. In operation, there are both minimum and maximum distances at which the thread 3 can be positioned away from the transducer device 6. Because of the finite speed of sound, this means that there is a range of time, after pulse transmission, outside which no valid reflection can be received. If the circuit is rendered non-sensitive outside this time span, there is no possibility of noise, false reflections, etc, giving erroneous results then.

Accordingly, the reflected signal is time gated by the microprocessor 11 so that only reflections from objects 27.5 to 42.5 mm away are taken into account.

The microprocessor 11 may also introduce a delay before the circuit indicates that a thread is not

present, to allow the thread to be removed by an operator for a short time, e.g. for inspection of the thread, without triggering the system that takes corrective action for a broken thread.

5 In the illustrated embodiment, the detection system looks for the thread (3) 125 times in a second. If it does not 'see' the thread for 2 seconds then it decides that the thread 3 is broken. The microprocessor 11 sends a message to a "host" system, i.e. a further control
10 system (not shown) that takes corrective action such as causing a solenoid to operate a brake on the 'roving', and activates the indicator light 7. Once the thread 3 has been mended, the sensor must 'see' it at least four times in a three-second period to decide that the thread
15 has indeed been mended. It then sends an appropriate message to the "host" system and switches off the indicator light 7.

 Such a decision system can ensure a low-error operation, and permits the yarn to be rethreaded without
20 confusing the corrective control system. The detection system is sensitive to signals of 70pV. This is achieved by careful noise-reduction and filtering.

 The cases of the sensor unit 1 and transducer 6, and a front electrode of that transducer are all connected to
25 a zero-potential pin (not shown). This provides a complete earth shield and so insulates the detecting system from capacitively coupled noise sources.

 The transducer device 50 of Fig. 5 includes a case 51, a backing layer 52, an active piezo-electric element
30 53 in contact with the backing layer 52, and an acoustic matching layer 54 in contact with a working face of the piezo-electric ceramic element 53. Respective connecting wires 55 are used to convey electrical signals to
 respective electrodes (not shown) on the said working
35 face and an opposite face of the element 53.

 In use of the device 50, the piezo-electric active element 53 serves to convert electrical oscillations into

mechanical vibrations and vice versa. The element 53 generally has its dimensions and constituent material chosen such that it resonates at the frequency of the acoustic waves be produced.

5 The matching layer 54 is provided to facilitate effective transfer of energy between the working face of the active element 53 and an external gaseous propagating medium. In practice it is found that because the acoustic impedances of practical piezo-electric materials
10 are several orders of magnitude greater than those of propagating media of interest (for example, air) energy transfer between the element 53 and the medium is very low unless a suitable matching layer 54 is present. According to conventional acoustic theory, when a
15 matching layer is interposed between two media the transfer of energy between the two media is greatest when the thickness of the matching layer is equal to one quarter of the wavelength of acoustic waves in the layer and when the acoustic impedance of the material of the
20 matching layer, at that wavelength, is equal to the geometric mean of the respective acoustic impedances of the two media.

The backing layer 52 serves to damp vibrations of the active element 53.

25 The transducer device of Fig. 5 may be used in a "pulse-echo" system in which, in a first (transmitting) operating mode, a burst of electrical driving signals of a predetermined ultrasonic frequency is applied to the piezo-electric element 53 via its electrodes so as to
30 cause the upper (working) face of that element (which is in contact with the matching layer 54) to vibrate at the said ultrasonic frequency, thereby causing acoustic waves to be propagated from the free face of the layer 54 into the adjacent air. In a second (receiving) operating
35 mode, commencing a predetermined time interval after termination of the said first burst of driving signals, the device 50 is used as a receiver of acoustic waves,

the incidence of such waves upon the free face of the matching layer 54 causing vibration of the piezo-electric element 53, whereby electrical signals in accordance with the received acoustic waves are produced in the connecting wires 55. By analysis of these electrical signals it is possible to determine whether or not an object is present at a target position a predetermined distance from the said working face.

In certain applications, such as detecting the presence of a thread in textile machinery, spatial restrictions make it necessary to arrange the transducer device very close to the object to be detected. In such a case, however, a problem arises in that the above-mentioned predetermined time interval, between the end of the transmitting mode and the start of the receiving mode, must be very short, because of the short time taken for acoustic waves to travel from the transducer to the object to be detected and back. Previously-considered transducer devices have not been capable of operating satisfactorily in such a pulse-echo system, because the time taken for oscillations to die away sufficiently for effective detection of received ultrasonic signals to be carried out is too great.

The device 50 of Fig. 5 may be regarded as a resonant oscillator whose sharpness in resonance may be described by its quality factor Q . The damping characteristics of any oscillator are characterised by its Q factor, which is the reciprocal of the fraction of the oscillator's energy lost in each cycle of oscillation.

A high Q is associated with a sharp resonance and consequently a high operating efficiency in converting electrical oscillations into acoustic waves and vice versa. A high Q is also, however, associated with a long decay time for residual oscillations following the removal of electrical drive signals. The number of cycles N required for oscillations to decay in amplitude

by a factor A may be expressed by the equation:

$$N = \frac{Q \ln A}{\pi}$$

Since at any given frequency the duration (period) T of each cycle is fixed, it follows that the time taken for oscillations to decay in amplitude by the factor A is given by:

$$t_{\text{decay}} = N T = \frac{Q T \ln A}{\pi} \dots\dots(1)$$

10

Thus, in short-range detecting applications, a difficulty arises in that although a high Q is desirable from the point of view of maximising operating efficiency, the higher the value of Q the higher the minimum separation of the object to be detected from the transducer device must be. For practical reasons, it is not always possible to simply increase that minimum separation, for example because space is not available or because the attenuation over the longer distances involved is too great for reliable detection of reflected ultrasonic waves.

20

The particular factors influencing the settling time will now be discussed in more detail.

The transducer device 50 of Fig. 5 consists of two resonant components, namely the piezo-electric element 53 and the matching layer 54, and two non-resonant components, namely the case 51 and the backing layer 52.

25

The case 51 does not perform any positive functions as an oscillator and should therefore be designed to oscillate as little as possible, and to isolate the device acoustically from a support member (such as a circuit board) on which the device is mounted. The case 51 may also function as a continuation of the backing layer 52.

30

The remaining components of the device 50 may be regarded as a set of acoustically-coupled oscillators, each of which oscillators has its own resonant frequency

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and damping characteristic. In the latter respect, each component is capable of storing energy and ringing (dissipating residual stored energy) even after electrical drive signals to the device have been removed.

5 In addition, since the components are in contact with one another, energy of oscillations will transfer between the different components, depending on their individual properties.

When electrical drive signals are removed from such

10 a set of coupled oscillators, residual energy is dissipated by a combination of energy loss in each individual oscillator, and by the transfer of energy from oscillators of naturally high Q to those with a lower Q. Thus, the particular overall Q value of a system of

15 oscillators, i.e. the overall transducer device, is dependent upon the internal absorption of energy of the individual oscillators and upon the transfer of energy between them

In a particular transducer device 50 for operation

20 with air as the propagating medium it is found that the factor which dominates the overall damping time of the transducer is the damping time of the matching layer 54. This is because the layer 54 is preferably made of a silicone rubber of low density, silicone rubber being an

25 optimal material for the matching layer because of its low acoustic impedance.

As mentioned above, the matching layer 54 should conventionally have an acoustic impedance which is equal to the geometric mean of the respective acoustic

30 impedance of the element 53 and the propagating medium, in this case air. Since typical piezo-electric materials have an acoustic impedance of approximately 3×10^7 Rayls ($\text{kgm}^{-2}\text{s}^{-1}$) and air has an acoustic impedance of only 400 Rayls, the impedance of the matching layer 54 should

35 conventionally be around 1.1×10^5 Rayls. However, no continuous homogenous solid having such a low acoustic impedance is known. The solid material with the lowest

known acoustic impedance is a low density silicon rubber, which at the generally preferred density of around $1.05 \times 10^3 \text{ kgm}^{-3}$ has an impedance of approximately 10^6 Rayls. Various transducer devices are available which employ a matching layer of such a silicone rubber. However, such devices are not suitable for operation over short ranges when the same device must be used both to transmit and receive ultrasonic acoustic waves. This is because the silicone rubber has a naturally high Q (low absorption), so that residual energy stored in the matching layer cannot be dissipated quickly enough for received ultrasonic waves, reflected back from an object to be detected, to be distinguished reliably from ringing effects.

In order to reduce the overall effective quality factor of the device 50 it is desirable to modify the effective quality factor of the dominating oscillator, in this case the rubber matching layer 54. Preferably also the respective quality factors of each of the component oscillators will not be unduly different in value from that overall effective quality factor.

Energy may be dissipated from the matching layer in three ways: dissipation into the air; transfer of energy into the piezo-electric element; and internal absorption. In practice, the most important dissipation process is that of energy transfer into the piezo-electric ceramic element. Considering this process in more detail, the quality factor Q_{rubber} of the rubber material may be expressed as

$$Q_{\text{rubber}} = \frac{-\pi}{2 \ln(R \alpha)} \dots\dots(2)$$

where R is the reflection coefficient at the piezo-rubber interface, and

$1/\alpha$ is the factor by which the amplitude of acoustic waves passing through the rubber is attenuated in a distance of one half of a wavelength.

From the above expression, it is apparent that Q_{rubber} may be reduced either by increasing the internal damping and thus lowering α , or by decreasing the reflection coefficient R .

5 The internal damping of the rubber may be increased by loading the silicone rubber material with a powder-form material such as fine glass powder, fly ash, plastic or metal powder.

10 The reflection coefficient R may be reduced by appropriately modifying the silicone rubber so that its acoustic impedance approaches that of the piezo-electric element. The acoustic impedance of a material is given by the product of the material density and the speed of propagation of acoustic waves (at the frequency of
15 interest) through the material. Accordingly, since the piezo-ceramic material has an acoustic impedance that is an order of magnitude greater than that of the rubber, one approach to reducing the reflection co-efficient at the ceramic/rubber interface is to increase the density
20 of the rubber material. As the density of the rubber increases the reflection of acoustic waves at the rubber/ceramic interface is reduced, so that during ringing more energy can escape from the rubber layer 5 to the piezo-electric element 53 which is damped by the
25 backing layer 52. Using this approach it is possible to optimise the transducer for sensitivity and short operating range.

As mentioned above, heretofore it has been the practice to employ as the material of the matching layer
30 a silicone rubber of a density around $1 \times 10^3 \text{ kgm}^{-3}$ (for example silicone rubber of the proprietary coding GE RTV615 manufactured by General Electric). In such a case, since the speed of propagation of ultrasonic waves through rubber material is 1000 ms^{-1} , the acoustic
35 impedance of the rubber is around 10^6 Rayls . In a device embodying to the present invention, however, the density of the rubber is increased to between 1.1 and 2.1 x

10³kgm⁻³, so that the acoustic impedance is increased proportionately to between 1.1 and 2.1 x 10⁶ Rayls. Accordingly, the reflection coefficient is reduced, lowering the effective quality factor Q_{rubber} of the rubber, so that the overall quality factor of the transducer is also reduced. Such a reduced overall Q can provide a value settling time that is sufficiently low to permit the transducer to operate reliably to detect objects placed at a distance of 12 mm or less from the device.

It will be appreciated that by further modifying the properties of the rubber matching layer it may be possible to provide a transducer capable of operating at even shorter ranges, such as 8 mm or less. In such a case, it may be necessary to employ a combination of material loading (to increase the internal damping) and increased rubber density to achieve the desired settling time.

By careful control of the material properties and design of the above-mentioned components of the transducer device, the applicants have found that it is possible to control the overall Q value of the transducer such that efficient operation is possible with a desirably short settling time. In this respect, it will be appreciated that when a device embodying the present invention is employed in a short-range detecting application, by virtue of its reduced settling time the minimum separation of the device from an object to be detected can be correspondingly reduced, so that the disadvantage conventionally associated with a reduced Q value, namely loss in operating range, does not represent a practical difficulty.

A specific example of a device embodying the present invention will now be described in more detail with reference to Figs. 6 and 7. In this example, the transducer device is required to operate reliably over a minimum range of 27.5mm. The frequency of operation is

chosen to be 1 MHz so as to provide a wavelength in air of acoustic waves of 0.33mm, sufficiently small to facilitate detection of threads of diameter as low as 0.1mm.

5 The time taken for acoustic waves to travel to and from an object at this minimum range is approximately 150 μ s. This corresponds to 150 cycles of oscillations at 1 MHz. Assuming that the amplitude of oscillations of the transducer is required to decay by a factor A of 5×10^5
10 (114 dB) in this number of cycles, it follows from equation (1) above that Q must be less than 36.

 The device of the present example is designed to have an overall Q factor close to 30. Such a value affords acceptable efficiency in transmission and
15 reception, but is small compared to the natural Q value of silicone rubber (of the order of 150 at the frequencies of interest).

 The device 50 includes a plastics casing, denoted generally at 51, of rectangular cross-section, which is
20 open at the rear. The casing 51 has respective tabs 60 projecting from its opposite ends. Each of the projecting tabs 60 has a locating pin 61 for engaging in a corresponding hole in a support member (not shown), such as a circuit board, by which the device is
25 supported. Because the pins 61 and tabs 60 are of relatively small area, the area of contact between the device and the support member is small, affording good acoustic isolation of the device from the support member. This is desirable to prevent the occurrence of parasitic
30 oscillations.

 Respective ribs 62 extend within the casing 51 through the entire height (perpendicular to the plane of Fig. 6) thereof.

 The casing 51 is formed at its front face with a
35 narrow rectangular slot 63 through which an elongate piezo-electric ceramic element 53 protrudes. The element 53 is 20.9 mm in length (l), 1 mm in height and 1.5 mm in

thickness. The thickness 1.5 mm of the element 53 (when the height is 1 mm) provides a structure with a resonant frequency of approximately 1 MHz since the wavelength of acoustic waves of this frequency (1 MHz) in the ceramic material is approximately 3 mm. The length of the element may be varied, but is chosen in dependence upon the desired extent of the area in which the presence of an object is to be detected.

The element 53 is preferably formed from a commercially available lead zirconate titanate ceramic material, of a "hard" (class 4) or "soft" (class 5) type. An example of a suitable lead zirconate titanate ceramic material is manufactured by Vernitron Division of Morgan Matroc under the proprietary code PZT5H. This material has a high operating efficiency at relatively high ultrasonic frequencies. The piezo-electric ceramic element 53 has a natural quality factor Q_{piezo} of about 60, and an acoustic impedance of 3×10^7 Rayls.

Respective front and rear electrodes 70 and 71 are formed on the front (working) and rear faces of the ceramic element 53. The front electrode 70, which extends along the entire length of the front face, has an end portion 72 which is wrapped around one end of the element 53 so as to provide a connection point on the rear face of the element. The rear electrode 71 does not extend along the entire length of the rear face of the element, but rather extends for a length of some 14 mm between the two ribs 62. Respective connection wires 55 are connected at their inner ends to the electrodes 70 and 71.

The rear interior portion of the casing 51 is filled with a backing layer 52 of synthetic resin, such as an epoxy resin. Polyurethane or other synthetic resins can alternatively be used. A suitable epoxy resin is known under the proprietary name "Devcon five-minute". The resin 52 surrounds the rear portion of the piezo-electric ceramic element 53. The resin 52 has a relatively low Q

value, and is closely coupled to surface areas of the element 53 so as to be capable of dissipating energy due to "ringing" in the piezo-electric element 53.

A rubber matching layer 54 extends over the front electrode 70. The thickness of the layer 54 is chosen to be equal to one quarter of the wavelength of ultrasonic waves passing through that layer. Thus, since for acoustic waves at a frequency of 1 MHz the wavelength of the waves passing through the silicone rubber layer 54 will be approximately 1 mm, the thickness of the layer 54 is preferably about 0.25 mm.

A suitable material for forming the matching layer 54 is low density silicone rubber manufactured by Dow Corning under the proprietary code 170. The density of the rubber in this embodiment is $1.38 \times 10^3 \text{ kgm}^{-3}$.

In use of the device of Figs. 6 and 7, the device is located on its support member at a distance of between 27.5 and 42.5 mm from the thread whose presence to be monitored. During a transmission mode of the device, a burst of thirty half-cycle pulses at a frequency of 1 MHz and an amplitude of 38 V is applied to the piezo-electric ceramic element 53 via the front and rear electrodes 70 and 71. Vibrations of the element 53 are then allowed to die away before, during a subsequent reception mode, ultrasonic waves scattered back from the thread are received by the transducer device, the piezo-electric element 53 being caused to vibrate in dependence upon such received waves and providing an output signal, in accordance with such received waves, between the connection wires 55. When coupled to appropriate signal processing circuitry, a sensitivity, to ultrasonic signals, of 70 μV at 1 MHz can be achieved.

Figs. 8(A) and 8(B) show the element 53 and the electrodes 70 and 71 of the transducer of Figs. 6 and 7 in more detail.

The front electrode 70 extends along the whole length of the working face of the element 53, and is

-20-

wrapped round one end of the element 53 so as to leave the end portion 72 of the electrode 70 extending 1 mm along the rear face of the element 53.

5 The rear electrode 71 does not extend along the entire length of the element 53, so that respective portions 73 and 74, of length 3 mm, of the rear face of the element 53 are not covered by the electrode 71.

The reason for using such electrode structures will now be explained with reference to Figs. 9 to 11.

10 Fig. 9 shows a simplified view of a typical detection arrangement employing a transducer device 80 having an elongate piezo-electric element 81 having respective front and rear electrodes 82 and 83 that extend fully along the front and rear faces of the
15 element 81. Electrical driving and receiving circuitry 84 is connected with the electrodes 82 and 83.

A thread 85 to be monitored is maintained under tension a small distance d from the transducer device 80, the device being disposed such that its longitudinal axis
20 extends perpendicularly to the axis of the thread 85. The spacing d of the thread 85 from the transducer device 80 is such that the thread occupies a target position in the near field of the device, which near field extends from the device for a distance $\ell^2/4\lambda$, where ℓ is the
25 length of the element and λ is the wavelength in air of emitted acoustic waves.

In use of the transducer device 80 the piezo-electric element 81 serves both as a transmitter and receiver of ultrasonic signals. Accordingly, in a first
30 operating mode electrical driving signals at a frequency substantially equal to the resonant frequency of the piezo-electric element 81 are applied to the electrodes 82 and 83 by the electrical driver and receiver circuitry 84. Such pulse signals cause the element 81 to expand
35 and contract in the forward/rearward direction so that the front (working) face of the element 81 having the electrode 82 is displaced in accordance with the

electrical pulse signals. Accordingly, acoustic waves are emitted from the front face of the device in the direction of the thread 85.

Subsequently, in a second operating mode the
5 electrical driver and receiver circuitry 84 becomes operable to receive electrical signals produced by the piezo-electric element 81 in accordance with the impingement thereon of acoustic waves scattered back by the thread 85 in the direction of the device 80. The
10 circuitry 84 analyses the received signals to determine whether they are consistent with the presence of the thread in the target region.

As mentioned hereinbefore, in practical thread detector arrangements it is not generally possible to
15 ensure that the position of the thread does not vary. Thus, the position of the thread 85 in Fig. 9 may vary from time to time in the forward/rearward direction of the device 80, and in directions parallel to the longitudinal axis of the device 80 (along a target line
20 shown at XX in Fig. 9).

In the case of the latter variation (along line XX) it is found in practice that the resultant amplitude of ultrasonic waves arriving at different positions along the line XX is not uniform, but exhibits a variable
25 characteristic as shown schematically in Fig. 10. The maximum amplitude of ultrasonic signals is produced at a position A directly opposite the longitudinal midpoint of the device 80. However, as shown in Fig. 10, the resultant amplitude diminishes rapidly as the distance
30 from the midpoint increases, such that at positions ("dead spots") denoted B and C respectively the resultant amplitude of the ultrasonic waves from the device 80 is much reduced as compared to the amplitude at the point A. As the distance from the position A increases further,
35 the amplitude rises again before falling to further minima at positions denoted D and E respectively.

When the thread 85 is located at the central

position A the resultant amplitude of the transmitted acoustic waves reaching the thread 85 is at its highest. Accordingly, a relatively strong reflected signal will be produced, which reflected signal will in turn give rise to a significant electrical signal for detection by the circuitry 84. However, as is clear from Fig. 10, since the resultant amplitude of the transmitted ultrasonic signals decreases rapidly as the thread is moved away from the central position A the detected electrical signal also decreases significantly. Eventually, near positions B and C, the detected signal may become indistinguishable from background noise.

Thus, the useful range of positions along the line XX in which a thread can be reliably detected using the Fig. 9 device is relatively small, perhaps only 10% of the length l of the transducer. The fact that the amplitude is sufficient between positions B and D, and between positions C and E, to permit detection of the thread is not of much practical value if it is not possible to detect the thread near to positions B and C.

The amplitude variation shown in Fig. 10 arises from diffraction and interference of the acoustic waves emitted from the transducer. In the Fig. 9 transducer device, each point on the front face of the device 80 acts as a point source of wavelets, the wavefront from each such point source being spherical. The wavelets emitted from the point sources have in principle the same frequency and amplitude of vibration and their vibrations are always in phase with one another. These sources are therefore "coherent" sources. Their combined effect at a given point is obtained by adding algebraically the displacements at the point concerned due to the sources individually; this is known as the Principle of Superposition.

At a position a very large distance from the individual sources, the distance from each individual source on the transducer front face to the position

concerned is substantially the same (that distance being very large compared to the dimensions of the transducer itself), so that the phase of all the wavelets reaching that position from the individual sources is also
5 substantially the same. At such a remote position, therefore, the transducer may be regarded as a single point source.

However, at a position near to the transducer the respective phases of the wavelets from the individual
10 sources reaching the position concerned vary from one another considerably according to the respective distances of the sources from that position. Accordingly, the wavelets interfere with one another constructively at certain positions (position A, D and E)
15 and destructively at other positions (for example positions B and C in Figure 9), giving rise to the amplitude profile shown in Fig. 10.

In the Fig. 9 arrangement, the thread 85 must be located relatively close to the transducer for reasons of
20 space and because the attenuation of ultrasonic signals at the high frequencies involved is relatively high. Thus, the transducer cannot be spaced from the thread by a distance sufficient to ensure that the transducer functions as a point source of ultrasonic waves.

25 To mitigate this problem, as seen in Figs. 8(A) and 8(B) the rear electrode 71 of the device of Figs. 6 and 7 does not extend over the portions 73 and 74, with the result that the amplitude of vibration produced by the end regions of the element 53 is less than that produced
30 in the remaining (central) region of that element. Thus, the amplitude profile of the device 50 of Figs. 6 and 7 is significantly different from that of the device 80 of Fig. 9. In particular, as shown in Fig. 11, the variation in amplitude is considerably reduced so that
35 the minima are no longer so pronounced. Thus, the amplitude at the first pair of minima to either side of the central position A' (at positions B' and C') is

significantly greater than the amplitude at the corresponding positions B and C in the Fig. 10 profile. Accordingly, "dead spots" do not occur at the portions B and C', because the amplitude at these positions is sufficiently great for reliable detection of returned waves.

Thus, because of the particular electrode structures shown in Figs. 8(A) and 8(B), the effects of the applied electrical driving signals differ at different locations along the front (working) face of the device 50 so as to counteract destructive interference effects that would otherwise occur at some points along the target line XX, thereby providing a useful range of positions, in which a thread can be reliably detected, that extends over approximately 70% of the length l of the transducer device.

Figs. 12 to 15 show respective side elevational views of alternative preferred elements and their associated electrodes for use in devices embodying the invention.

In Fig. 12 a piezo-electric element 90 is provided on one face thereof with a single continuous electrode 91, the electrode structure 92 on the opposite face of the element 90 being composed of five separate mutually-spaced portions 92a to 92e. Each of the portions 92a to 92e, however, receives the same electrical signal. As compared to the arrangement shown in Figs. 8(A) and 8(B), it is apparent that the arrangement of Fig. 12 is more complex, but can provide more sophisticated control of the amplitude profile.

A piezo-electric element 100 of Fig. 13(A) also has a continuous electrode 101 along one face thereof but has a plurality of individually-driven separate electrode portions 102a to 102k on its opposite face. The respective drive voltages to the portions 102a to 102k differ from one another as shown in Fig. 13(B). The individual electrode portions 102a to 102k may be formed

by depositing a single continuous electrode on the face of the element concerned and then scribing that continuous electrode. The electrode 101 may also be provided as a plurality of individual electrode portions.

5 In Fig. 14, a piezo-electric element 110 again has a single continuous electrode 111 extending along the full length of one face, but at the opposite face a dielectric layer 112 is interposed between a second electrode 113 and the element 110. The thickness of the layer 112
10 increases progressively in both longitudinal directions away from the longitudinal mid-point of the element 110.

In Fig. 15(A) a bare piezo-electric element 120 is prepared by temporarily contacting opposite sides thereof with respective first and second poling electrodes 121
15 and 122. The first poling electrode 121 extends along the full length of the element 120, but the second poling electrode 122 only extends over a central longitudinal region thereof. The poling electrodes 121 and 122 may be conductive rubber pads, for example. A high d.c. voltage
20 of for example 2000-3000V is applied between the electrodes 121 and 122 for a short period, of several minutes duration for example, the temperature of the element 70 being elevated during this period to perhaps 90°C. Thereafter, the poling electrodes 121 and 122 are
25 removed and then, as shown in Fig. 15(B), full continuous electrodes 123 and 124 are mounted on opposite faces of the element 120. In use of the element 120 of Fig. 15(B), the poorer poling of the element 120 at its ends gives rise to the preferred amplitude profile.

30 It will be appreciated that the electrode structures shown in Figs. 8(A) and 8(B), and in Figs. 12 to 15, can also be applied effectively to other forms of electro-acoustic elements, such as electrostatic elements, to enable the amplitude profiles of those other elements to
35 be similarly modified.

For reasons explained below with reference to Figures 16 to 19, the transducer has a preferred height

of 1.0 mm, this being the narrower dimension of the elongate working face of the piezo-electric element.

It is to be noted that the thread is located in the far field region of the vertical field of view of the transducer. This region starts at a distance from the transducer defined by $\frac{D^2}{4\lambda}$ where D

is the height of the transducer.

For example for a transducer of height D generating sound with wavelength λ , the sound wave generated will correspond to the diffraction pattern generated by a plane wave striking a slit of height D. It will thus consist of a primary lobe with half-angle θ given by:

$$\sin \theta = \frac{\lambda}{D} \quad \text{Equation A}$$

and a number of secondary lobes as seen in Fig. 16.

The sound wave will travel to the thread 3 which is disposed at an angle α to the vertical, and be reflected back towards the transducer. As can be seen from Figure 16, the amplitude of the primary lobe is far greater than that of the secondary lobes. Thus if any appreciable signal is to be received, sound from the primary lobe must be reflected back onto the transducer. As can be seen from Figure 17 the upper section of the beam, travelling with a wave-front at an angle θ to the vertical will strike the thread 3, which is at an angle α to the vertical, and be reflected so that the beam is travelling at an angle of $(2\alpha - \theta)$ to the vertical. This part of the beam will reach the transducer at a height $2d(\alpha - \theta)$ below the transducer. For the beam to hit the transducer, this distance must be less than half the transducer height. i.e.

$$2d(\alpha - \theta) < \frac{D}{2}$$

As mentioned, d may be as great as 42.5 mm and α as great as 10° . Using the operating frequency of the

device of Figs. 6 and 7, i.e. 1 MHz then, substituting for θ using Equation A:

$$\frac{D}{2} + \frac{28}{D} > 15$$

5

This means that

$$\begin{aligned} D &< 2.0 \text{ mm} \\ \text{or} \quad D &> 28 \text{ mm} \end{aligned}$$

10

When D is greater than 2.0 mm, for example 5 mm, as shown in Figure 18, a narrow sound cone is generated from the transducer which misses the transducer after reflection by a thread 3 angled at 10° .

15

A further constraint is that, to avoid destructive interference, the phase of the returning signal should vary by significantly less than one cycle across the surface of the transducer. That is that:

$$D \alpha < \lambda$$

20 or substituting for α and λ

$$D < 1.9 \text{ mm}$$

Thus, by choosing D to be less than 1.9 mm, it can be ensured that, when the filament is at its greatest angle, 10° , the reflected beam strikes the transducer and the

25

components across the surface do not interfere destructively. It is important however, that the beam is not too divergent (as shown in Fig. 19) as this will reduce the received signal amplitude. As can be seen, the wide cone created by the transducer (which is 0.5 mm high) allows detection of threads which are disposed at angles from the vertical, but only a small fraction of the reflection is received by the transducer. If the beam has a half angle of θ then the fraction of the wavefront falling on the transducer is:

35

$$\frac{D}{41\theta} = \frac{D^2}{41\lambda}$$

As the amplitude is also proportional to D, the size of the aperture, the result is that the pressure amplitude of the received signal goes as:

40

$$D^3$$

-28-

41λ

For this reason the transducer height, D , must be chosen to be the largest value consistent with $\theta > \alpha$.

5 A further constraint on D comes from considerations concerning the piezo-ceramic resonant modes. It is well established that a piezo will operate efficiently when the height, D , is approximated one half its thickness, t , and inefficiently when the height is approximately equal
10 to its thickness. For operation at 1MHz a thickness of 1.5 - 1.8 mm is required (depending on the height) and thus for efficient operation it is wise to choose a height between 1.0 and 0.75 mm.

15 It has therefore been found that a height of 1.0 mm gives efficient transduction while generating sound with a suitable cone angle.

20 It can therefore be seen that using a combined theoretical and empirical approach it has been established that a transducer whose height is 1 mm allows sound to be transmitted and received over a suitable range of thread angles. If the transducer is too high then two effects reduce the angular performance, geometric shadowing and interference. With geometric shadowing a collimated beam is reflected specularly from
25 an angled thread and so misses the transducer.

 If the phase of the reflected beam varies by one cycle over the height of transducer then it will interfere destructively. These two effects combine to reduce the height.

30 However if the transducer is made too narrow then the transmitted acoustic energy will be reduced and reduce signal strength unnecessarily.

-29-

CLAIMS:

1. An ultrasonic electro-acoustic transducer (50) comprising an electro-acoustic element (53) having an elongate working face, bearing a first electrode structure (70), and a second face spaced from the said working face and bearing a second electrode structure (71);
- there being electrical driving circuitry connected to the first and second electrode structures for applying electrical driving signals therebetween to cause the element to vibrate so that ultrasonic acoustic waves are propagated, into a medium coupled to the said elongate working face, in a direction away from that working face;
- and the said electro-acoustic element, electrode structures and driving circuitry being such that the effects of the said electrical driving signals differ at different locations along the said working face so as to counteract destructive interference effects that would otherwise occur at points, in the said medium, along a target line parallel to the said longitudinal axis and spaced at a predetermined distance in the said direction from the said working face.
2. A transducer as claimed in claim 1, wherein the said working face and the said second face are of substantially the same dimensions.
3. A transducer as claimed in any preceding claim, wherein the said first electrode structure comprises a first electrically-conductive strip (70) extending over the full length of the said elongate working face, and the said second electrode structure comprises a second electrically-conductive strip (71) extending over only a central portion of the said second face.
4. A transducer as claimed in claim 3, wherein the respective widths of the said first and second electrically-conductive strips (70, 71) are substantially equal to the widths of the said elongate working face and

the said second face respectively.

5. A transducer as claimed in claim 3 or 4, wherein the length of the said second electrically-conductive strip (71) is substantially two-thirds of the length of the said second face.

6. A transducer as claimed in any one of claims 3 to 5, wherein the respective widths of the said first and second electrically-conductive strips (70, 71) are substantially the same.

7. A transducer as claimed in claim 1 or 2, wherein the said first electrode structure comprises a first electrically-conductive strip (91) extending over the full length of the said elongate working face and the said second electrode structure comprises a plurality of separate further electrically-conductive strips (92a, 92b, ... 92e) extending over different respective longitudinal portions of the said second face.

8. A transducer as claimed in claim 7, wherein the said electrical driving circuitry is operable to apply substantially the same electrical driving signals to each of the said further electrically-conductive strips (92a-92e).

9. A transducer as claimed in claim 7, wherein each of the said further electrically-conductive strips (102a-102k) is of substantially the same length, and the said electrical driving circuitry is operable to apply different respective electrical signals to the said further electrically-conductive strips (102a-102k) such that the electrical potential differs at different locations along the said second face when the transducer is in use.

10. A transducer as claimed in claim 9, wherein the said different respective electrical driving signals are such that the respective electrical potentials between the said further electrically-conductive strips (102a-102k) and the said first electrically-conductive strip (101) decrease successively in the outward directions

-31-

from a central location along the longitudinal axis of the said second face towards the ends of that face.

11. A transducer as claimed in claim 1 or 2, wherein the said first electrode structure comprises a
5 first electrically-conductive strip (111) extending over the full length of the said elongate working face, and the said second electrode structure comprises a dielectric strip (112) formed on the said second face and a second electrically-conductive strip (113) formed on
10 the said dielectric strip, the thickness of the said dielectric strip (112) increasing progressively in the outward directions from a central location along the longitudinal axis of the said second face towards the ends of that face.

15 12. A transducer as claimed in claim 1 or 2, wherein the said first and second electrode structures comprise respective electrically-conductive strips (123, 124) extending along the full length of the said elongate working face and the said second face respectively, the
20 said electro-acoustic element (120) having been selectively poled at different locations along the longitudinal axis of the element by temporarily contacting the said elongate working face and the said second face of the element (120) with respective poling
25 electrodes (121, 122) having a predetermined potential difference therebetween.

13. A transducer as claimed in claim 12, wherein the said poling electrodes (121, 122) were electrically-conductive rubber pads.

30 14. A transducer device as claimed in claim 12 or 13, wherein the temperature of the said element (120) was elevated during such poling.

15. A transducer as claimed in any one of claims 12 to 14, wherein the ends of the element were poled less
35 than a central portion thereof.

16. A transducer as claimed in any preceding claim, wherein the said electro-acoustic element (53) is a

-32-

piezo-electric ceramic element.

17. A transducer as claimed in any preceding claim, wherein the frequency of the said acoustic waves is in the range from 0.8 to 1.2 MHz.

1/9

FIG.1.

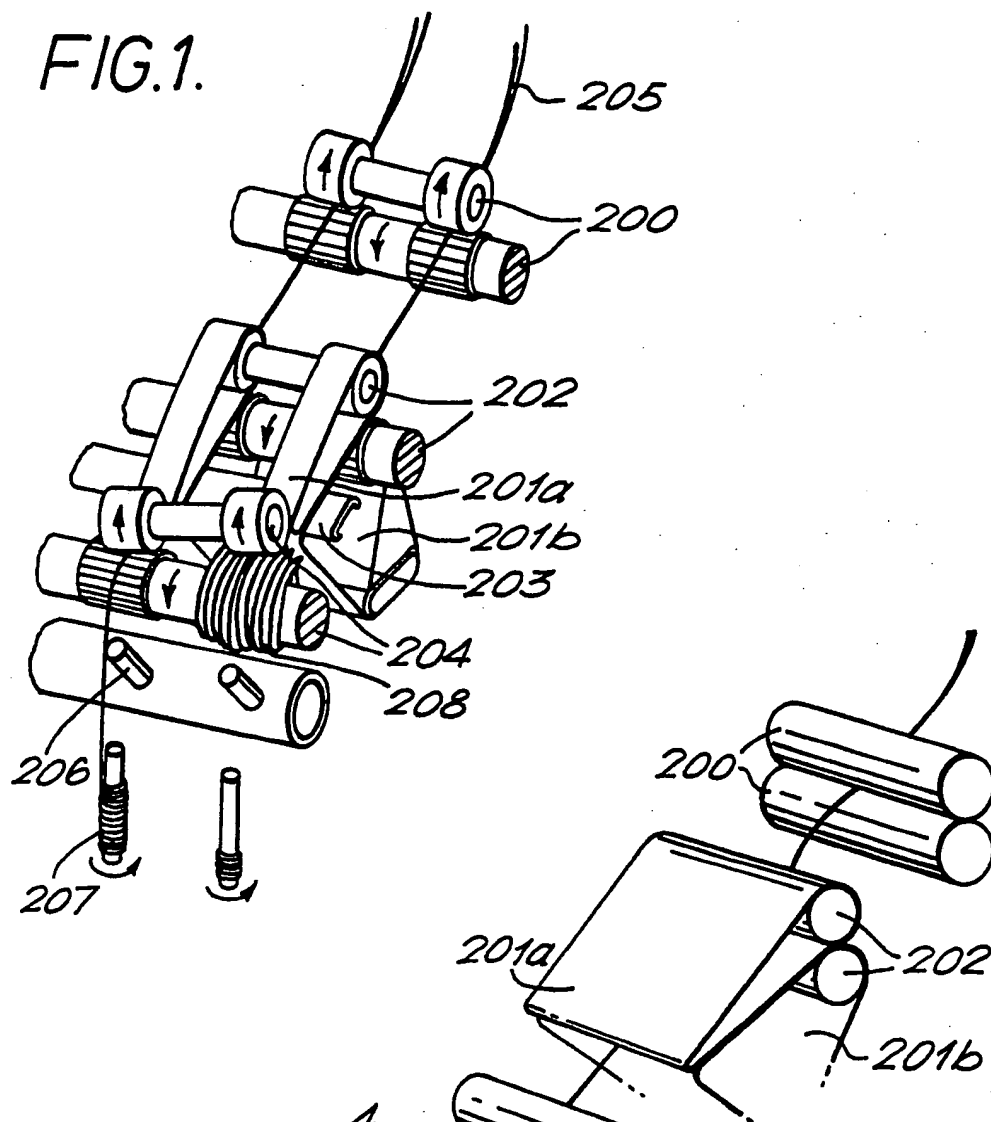
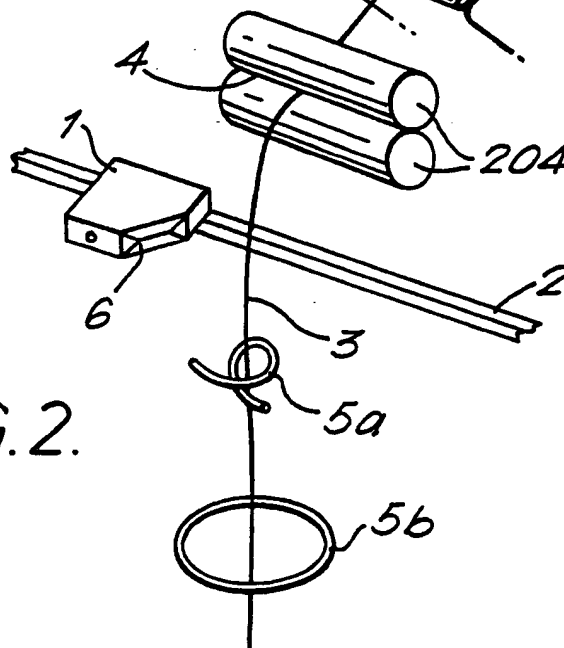
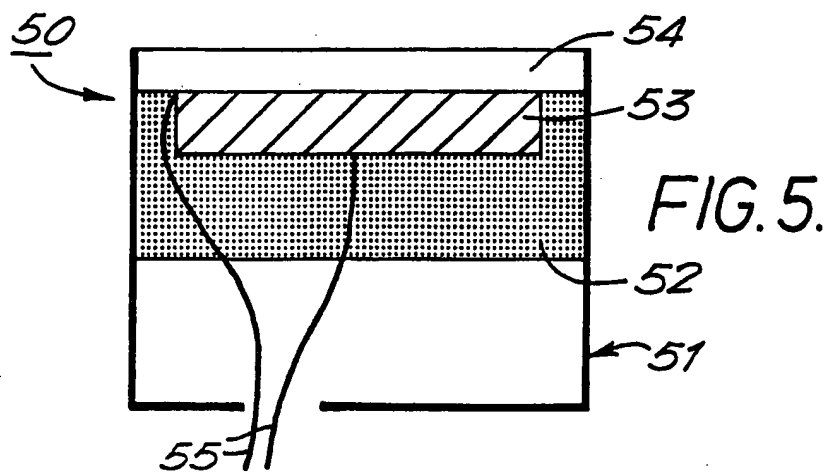
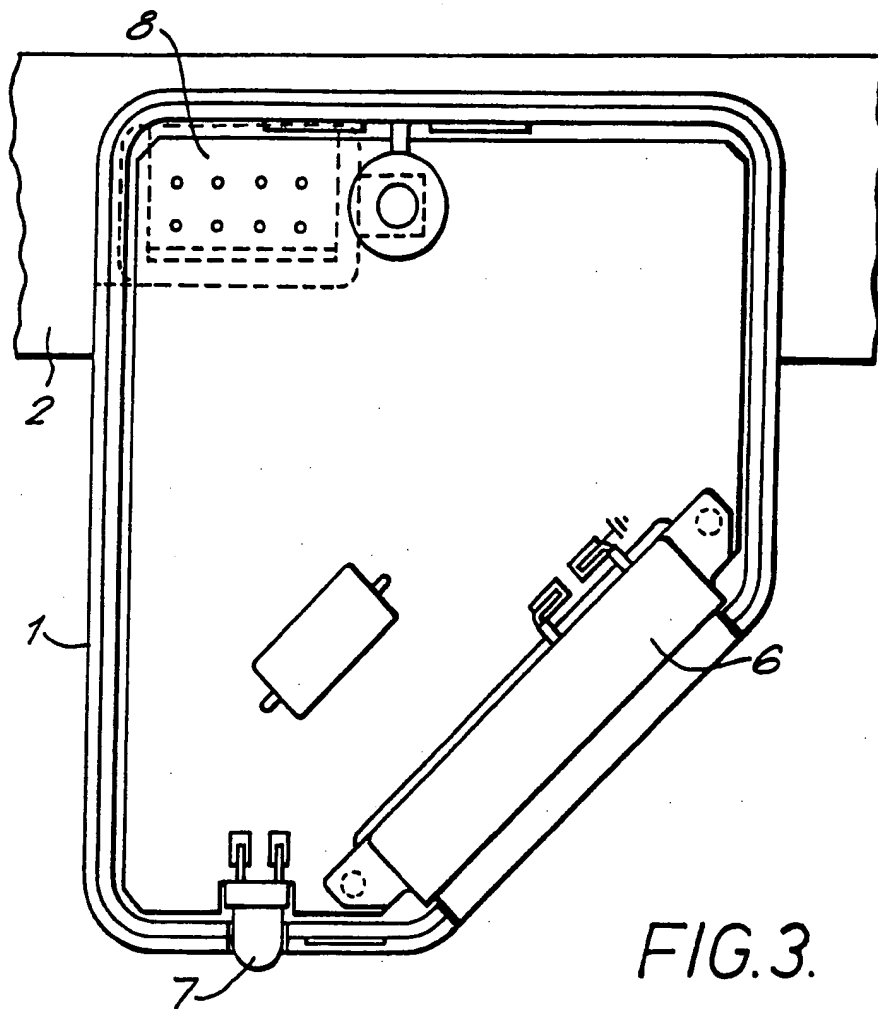


FIG.2.



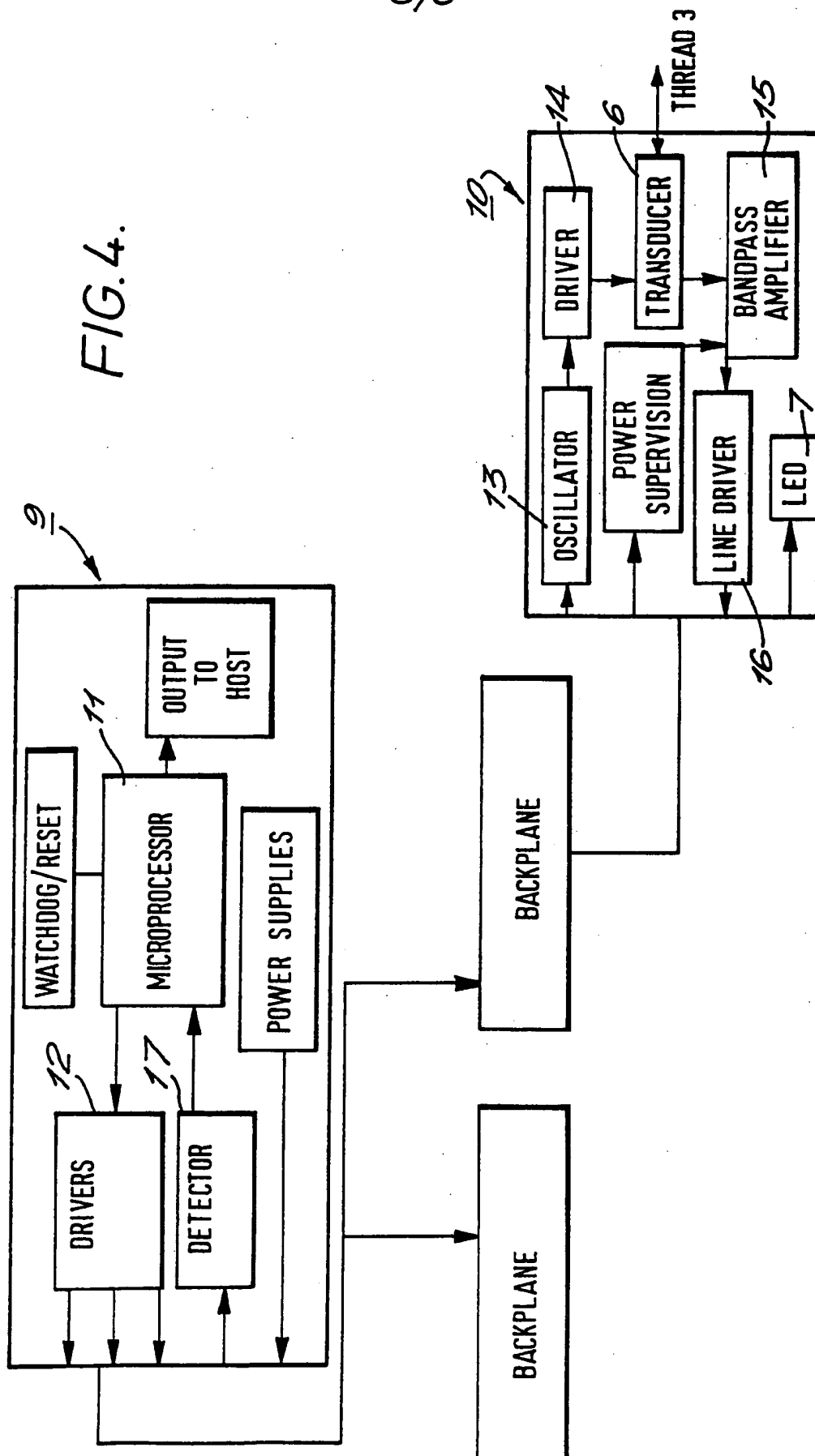
SUBSTITUTE SHEET

2/9



3/9

FIG. 4.



4/9

FIG.6.

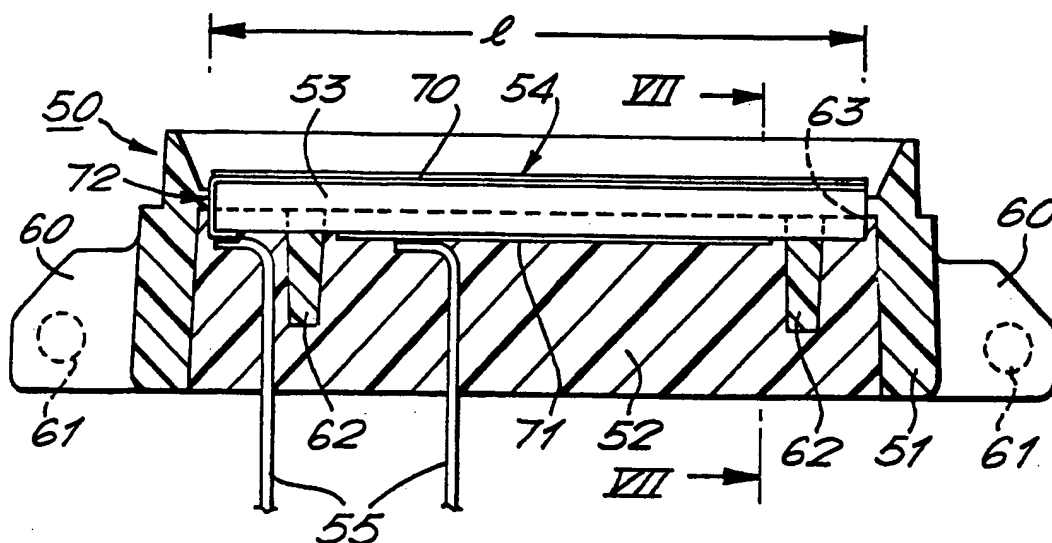


FIG.7.

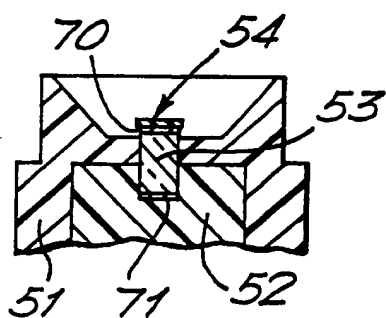


FIG.8(A)

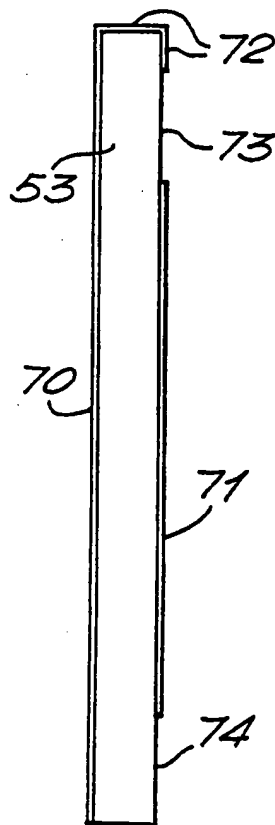
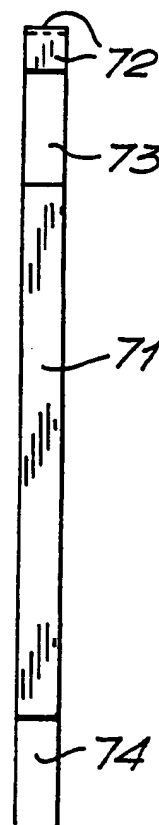
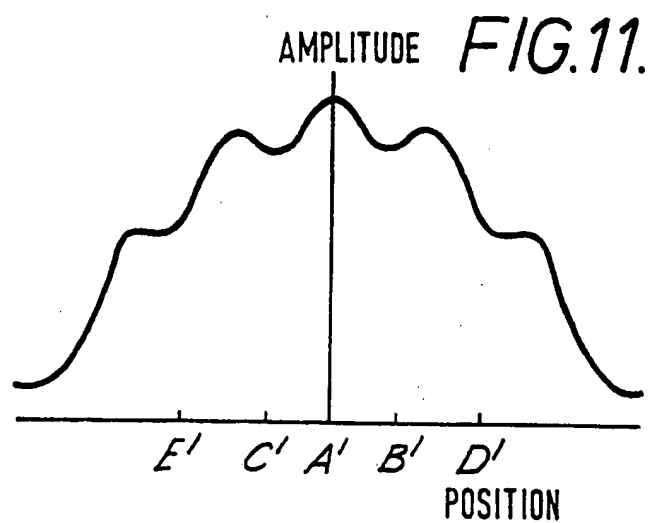
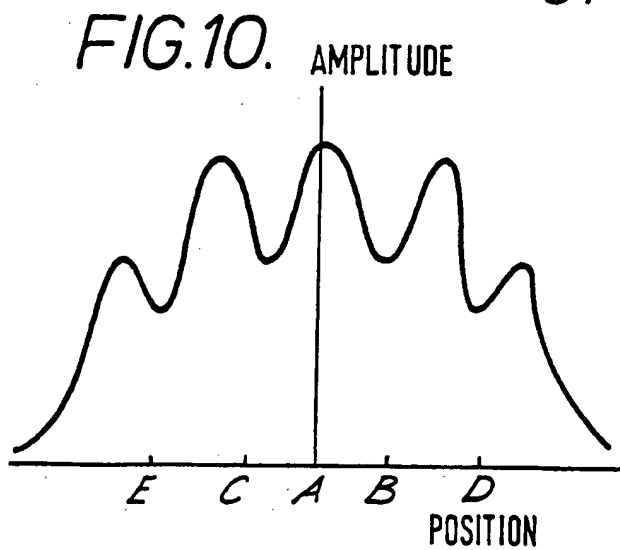
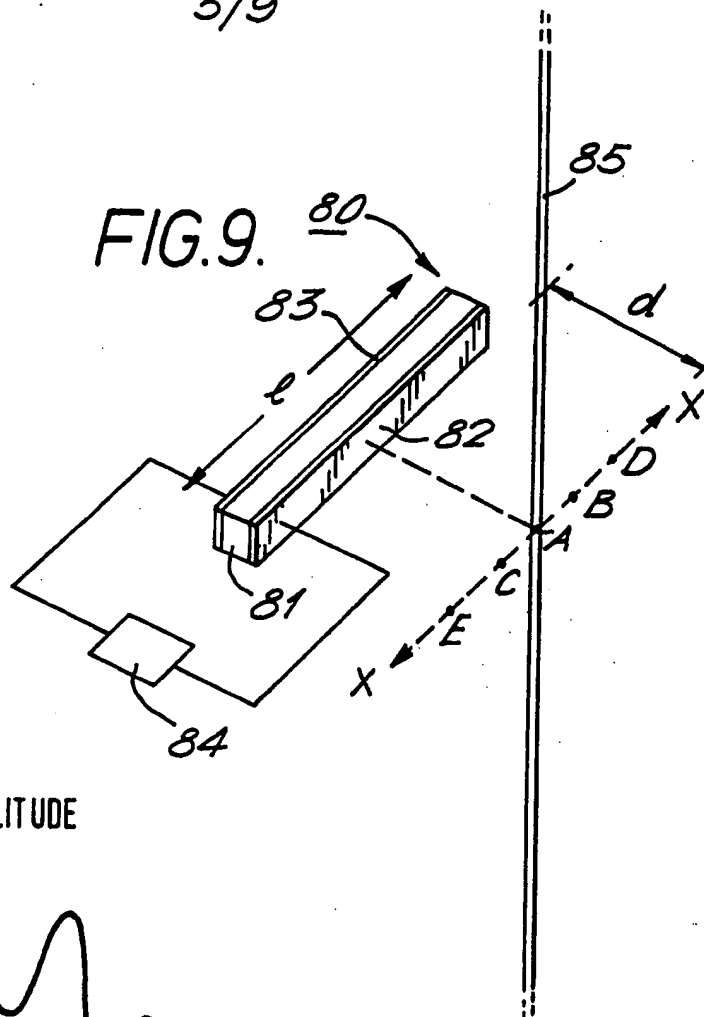


FIG.8(B)



5/9



6/9

FIG.12.

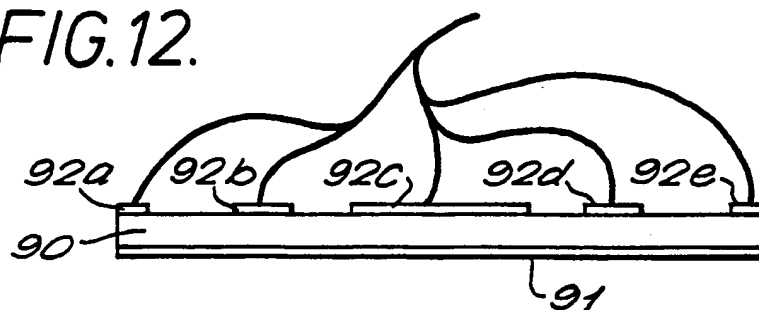


FIG.13(A)

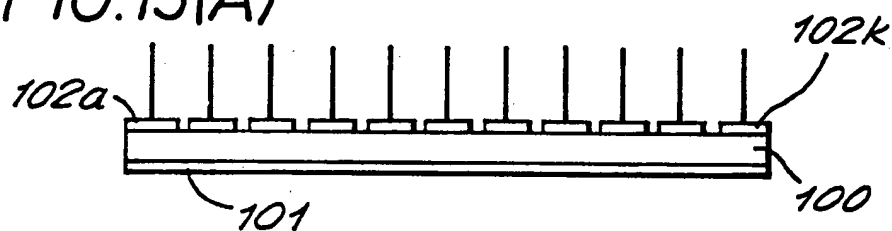


FIG.13(B)

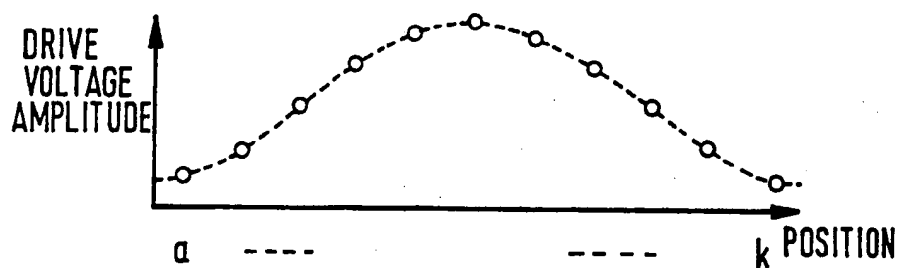
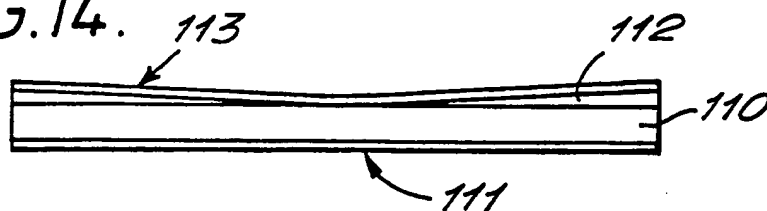


FIG.14.



7/9

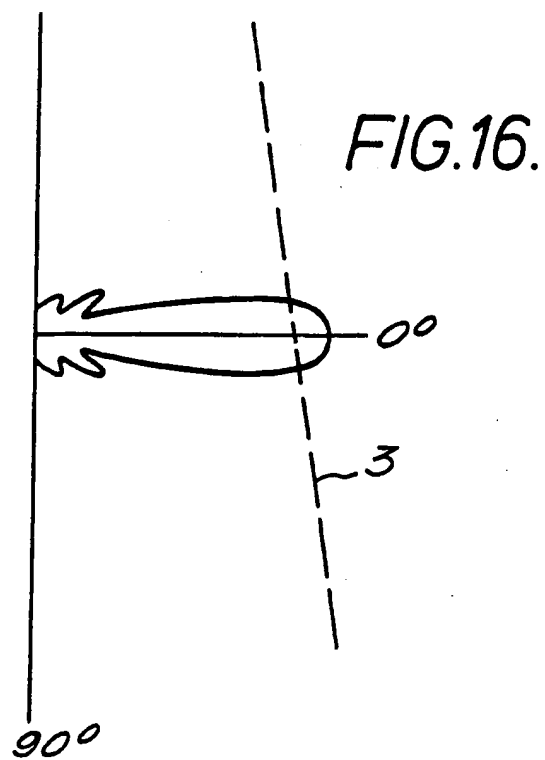
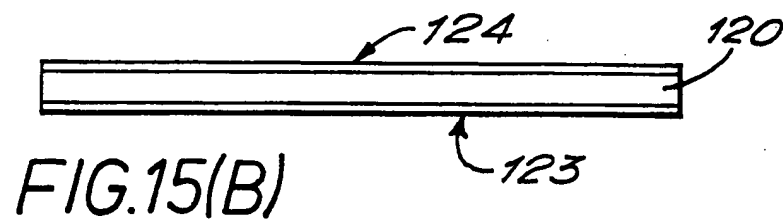
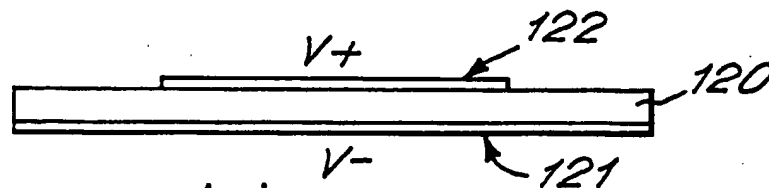


FIG.17.

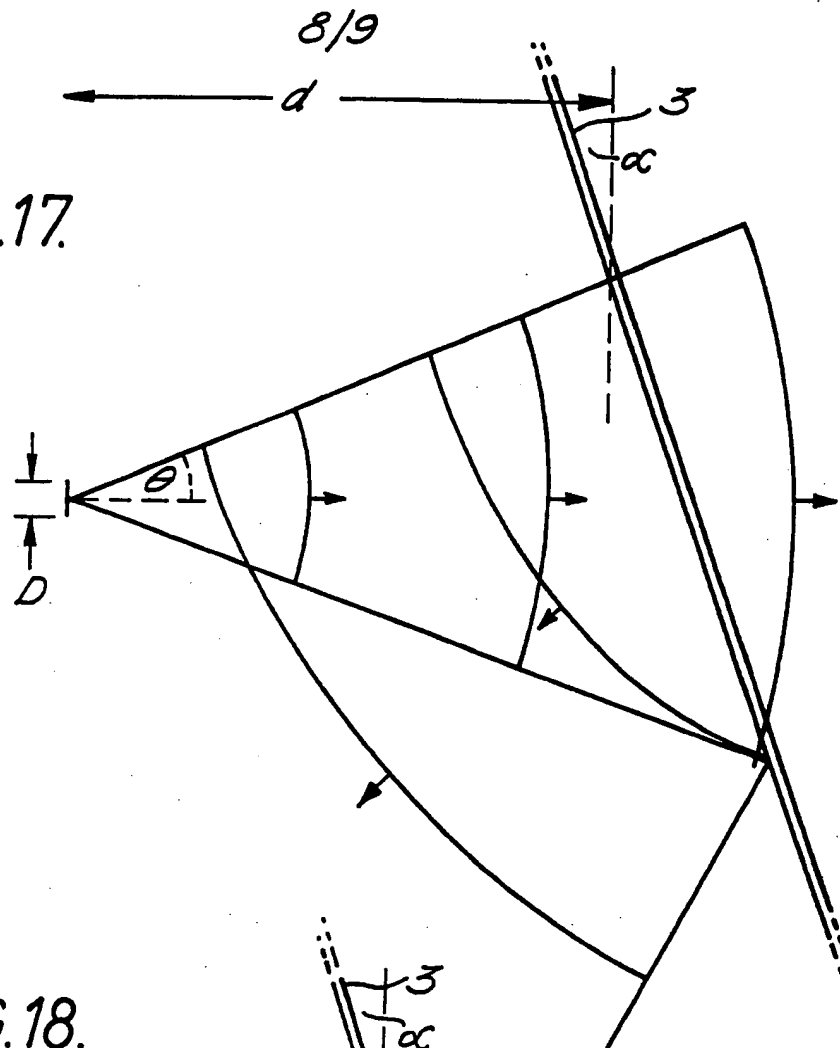
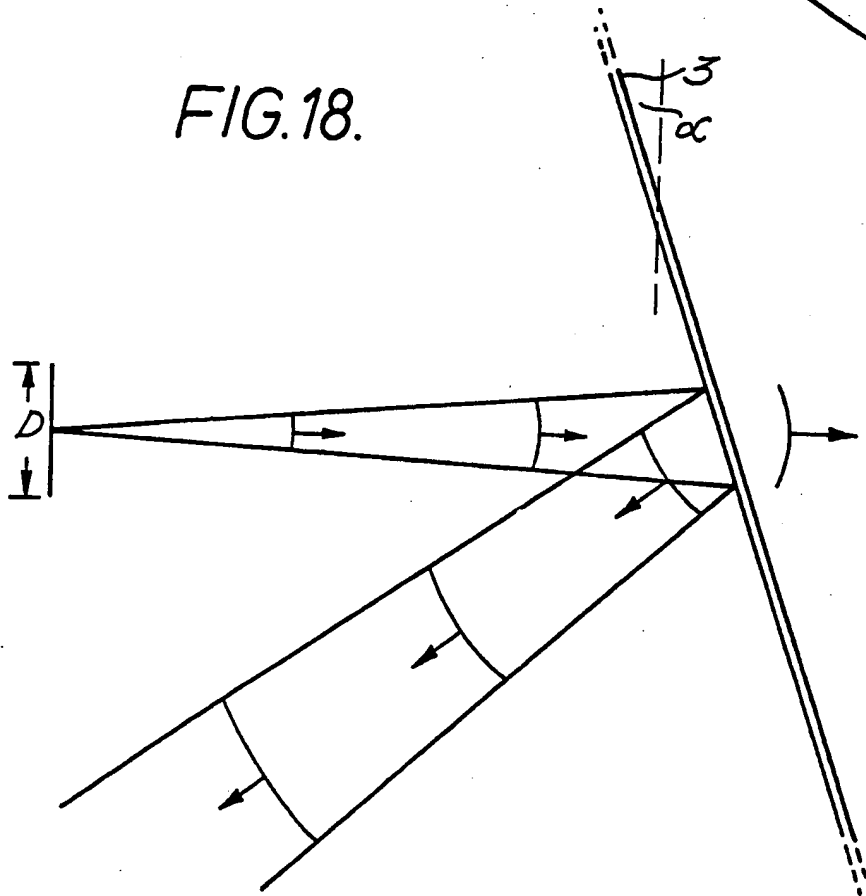


FIG.18.



9/9

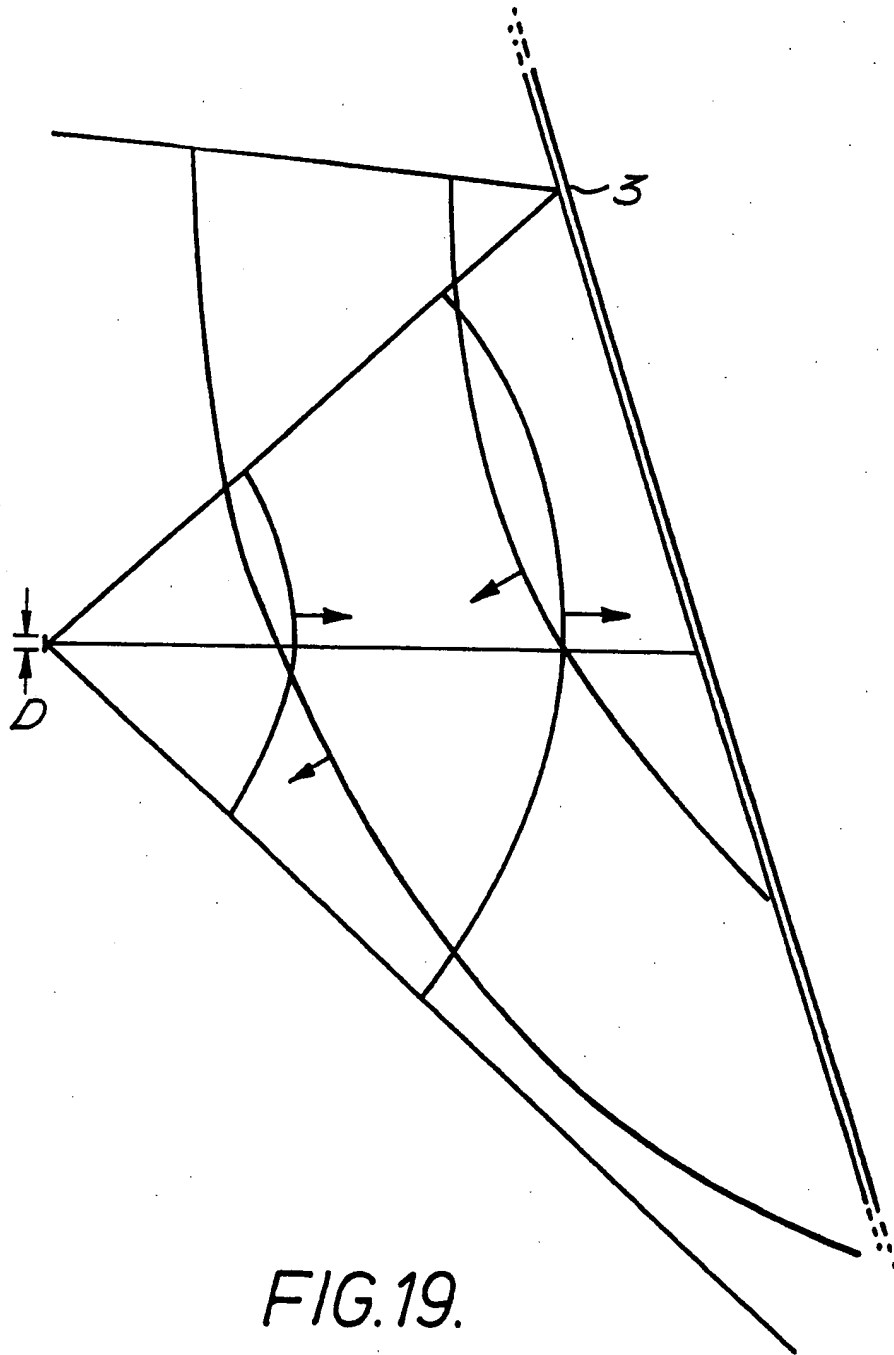


FIG.19.

INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 91/01256

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)⁸

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.C1.5 B 06 B 1/06

II. FIELDS SEARCHED

Minimum Documentation Searched⁷

Classification System

Classification Symbols

Int.C1.5

B 06 B

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched⁸

III. DOCUMENTS CONSIDERED TO BE RELEVANT⁹

Category¹⁰

Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages¹²

Relevant to Claim No.¹³

A	US,A,3025419 (METTLER) 13 March 1962, see figures 2-4 ---	1-6
A	US,A,4446396 (CLAUS et al.) 01 May 1984, see figures 2,3 ---	9-10
A	GB,A,2190818 (AKTIESELSKABET BRUEL + KJAER) 25 November 1987, see abstract; figure 5 ---	11
A	US,A,3374367 (COWAN) 19 March 1968, see claim 1 -----	12

¹⁰ Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search

22-10-1991

Date of Mailing of this International Search Report

11. 11. 91

International Searching Authority

EUROPEAN PATENT OFFICE

Signature of Authorized Officer



Danielle van der Haas

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

GB 9101256
SA 49595

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